What is the Scale of Supersymmetry Breaking?

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For a long time, it has been widely assumed that if the underlying laws of nature are supersymmetric, supersymmetry is broken at a scale intermediate between the weak scale and the Planck mass. The construction of realistic models of dynamical supersymmetry breaking in which supersymmetry is broken at a much lower scale, as well as a growing appreciation of the supersymmetric flavor problem has reopened this question. After reviewing some ideas for understanding the microscopic origin of the soft breaking parameters in the context of string theory, I turn to low energy breaking. Independent of the details of the underlying theory, events with photons and missing energy, like the CDF $e^+e^-\gamma\gamma \not{E}_T$ event, are likely signals of low energy breaking. I briefly review the predictions of the simplest model of low energy supersymmetry breaking for the soft breaking parameters (MGM), and then ask what sorts of generalizations are possible. It turns out that if all couplings are weak, there are only a limited number of ways to modify the model.

1. Introduction

In thinking about supersymmetry phenomenology, there are (at least) three reasonable approaches to the question: what is the origin of supersymmetry breaking? The first is to ignore the question, and simply study a supersymmetric theory with explicit soft breakings[1]. This approach, while pragmatic, can hardly be predictive. In the case of the minimal supersymmetric standard model, for example, there are 106 parameters. Typically, in order to make progress, one makes a simple ansatz for these, such as degeneracy of the squark mass matrix at some high energy scale and proportionality of the soft trilinear couplings to the fermion Yukawa couplings. This automatically satisfies the constraints from various flavor changing processes.

A closely related approach is based on $N = 1$ supergravity. Here one assumes supersymmetry breaking in a hidden sector, with F and D components of some chiral and vector fields obtaining vev's at a scale of order 10^{11} GeV[2]. However, these models still possess 106 parameters, which correspond to terms in the Kahler potential and gauge coupling functions involving hidden sector fields. Typically one assumes again degeneracy and proportionality at the highest energy scale. However, only if one has a microscopic theory which explains these parameters does one have a truly predictive framework, in which one can evaluate the plausibility of such assumptions.[2] Of course, the only microscopic theory of (super) gravity which we presently know is string theory. As I will briefly review, within our current understanding, string theory offers support both to optimists and pessimists on this issue. Alternatively, one can ask whether, lacking a detailed understanding, symmetries might help in solving the supersymmetric flavor problem and reducing the number of parameters[3] [4][5]. Here, there has been somewhat greater success, as we have heard at this meeting[6].

The third possibility is that supersymmetry is broken at low energies, and that gauge interactions are the "messengers" of supersymmetry breaking[7][8] [9]. As I will discuss in more detail, this approach has a number of virtues:

- It is highly predictive. The soft breakings can all be computed in terms of two or three parameters

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[2] Mass differences in these theories receive ultraviolet divergent radiative corrections, as is appropriate for *parameters* of a model.

- The degeneracies required to suppress flavor-changing neutral currents are automatic.
- This framework readily incorporates dynamical supersymmetry breaking, and thus offers promise of explaining the hierarchy.
- For a broad range of parameters, low energy, gauge-mediated supersymmetry breaking makes distinctive and dramatic experimental predictions.

Existing models still suffer from certain drawbacks. Perhaps the most serious of these is the μ problem[8][9] [10]. While several solutions have been offered, none yet seems compelling (see the talk by Pomarol at this meeting for a discussion of this problem).

2. Supersymmetry Breaking in String Theory

All known classical string vacua possess moduli. The problem of supersymmetry breaking in string theory is the problem of undersanding the lifting of these flat directions. Inevitably, whatever potentials are generated – by instantons, gaugino condensation, or other mechanisms – fall to zero in regions of the moduli space where a weak coupling description is possible[11]. Thus stabilization of the moduli must occur, if it occurs at all, in regions of strong coupling.

But there are phenomenological reasons to think that if string theory does describe nature it sits far from the region of weak coupling. In particular, one's naive expectation is that if R is the compactification radius and T the string tension,

$$\alpha_{GUT} = \frac{\alpha_{string}}{R^6 T^3} \tag{1}$$

If we identify $R = M_{GUT}^{-1}$, then $\alpha_{string} > 10^6$! The various known duality transformations take the heterotic string at such very strong coupling and large radius to moderate coupling in other theories[12]. Witten has pointed out that in the large radius limit one expects that "M theory," should provide a better description of physics than weak coupling strings[13]. ¿From the perspective of M-theory, the relevant parameters are the eleven dimensional Planck mass, M_{11}, the radius of the eleventh dimension, R_{11}, and the compactification radius (unification scale), R. These first two quantities can be determined in terms of the four dimensional Planck mass and the gauge coupling (interpreted as the unified coupling at the scale R). One finds, taking $R^{-1} \approx 3 \times 10^{16} GeV$, that

$$R_{11} M_{11} \approx 8 \qquad R M_{11} \approx 2. \tag{2}$$

While it is not necessarily germane to the issue of universality which we are addressing here, it is worth pausing to note that this has the striking implication that all of the important scales of the theory are of order M_{GUT}. This fact has implications for proton decay, the strong CP problem, and other questions.

What does string theory have to say about the question of universality? In the weak coupling limit, it has been known for some time that, if the dilaton dominates supersymmetry breaking, one gets approximate universality [14]. It turns out that in the eleven dimensional limit, one also obtains universality under certain conditions[15]. In both cases, taking the weak coupling picture literally, the degree of universality is at best just barely consistent with the bounds from flavor changing effects[16]. However, it is unlikely that stabilization of the moduli can occur in a regime where the coupling is weak; corrections to the Kahler potentials of the various fields – and, as a result, the corrections to the soft breaking terms – are almost certainly large. In both the very weak and very strong coupling limit, then, the assumption of weak coupling is incompatible with stabilization of the moduli[15]. One can summarize the situation of high scale breaking in string theory by saying that there are hints for possible sources of universality, but no clear and compelling picture really exists. Flavor symmetries, at present, seem to provide a more promising solution of the supersymmetric flavor problem in the context of high scale breaking.

3. Low Energy Dynamical Supersymmetry Breaking

Over the last few years, realistic models have been constructed in which supersymmetry is dynamically broken at low energies[8,9]. In these models, the messengers of supersymmetry breaking are ordinary gauge interactions ("Gauge Mediated Superymmetry Breaking," or GMSB). In the minimal model of this kind (MGM), the messengers have the quantum numbers of a 5 and $\bar{5}$ of $SU(5)$. They couple to a singlet field, S, through a superpotential

$$k_1 S q \bar{q} + k_2 S l \bar{l}. \tag{3}$$

Due to interactions with some supersymmetry breaking sector of the theory, the scalar and F-components of S, $\langle S \rangle$ and $\langle F_S \rangle$ are non-vanishing. Gaugino masses arise at one loop; scalar masses at two loops. They are given respectively, by the expressions:

$$m_{\lambda_i} = c_i \ \frac{\alpha_i}{4\pi} \ \Lambda \ , \tag{4}$$

$$\tilde{m}^2 = 2\Lambda^2 [\ C_3 \left(\frac{\alpha_3}{4\pi}\right)^2 + C_2 \left(\frac{\alpha_2}{4\pi}\right)^2 + \frac{5}{3}\left(\frac{Y}{2}\right)^2 \left(\frac{\alpha_1}{4\pi}\right)^2], \tag{5}$$

where $\Lambda = \langle F_S \rangle / \langle S \rangle$, $C_3 = 4/3$ for color triplets and zero for singlets, $C_2 = 3/4$ for weak doublets and zero for singlets, and Y is the ordinary hypercharge.[3] In this model, the A terms are high order effects. The μ and $B\mu$ parameters can arise through interactions of the Higgs fields with various singlets[9].

This model is quite simple. At low energies, the only new parameters relative to the minimal standard model are Λ, μ and $B\mu$. Because in the leading approximation scalar masses are functions only of gauge quantum numbers, flavor changing processes are automatically suppressed. A negative mass for H_U arises through top quark loops and gives rise to $SU(2) \times U(1)$ breaking, in a manner similar to that in more conventional theories. Because one does not need to run the renormalization group equations over too many decades in energy, one can write the following approximate expression for the Higgs mass:

$$(m_{H_U})^2 = (m^o_{H_U})^2 - \tfrac{6 y_t^2}{16\pi^2} \ln(\Lambda^2/\tilde{m}_t^2)(m^o_t)^2 \tag{6}$$

Note that while the coupling is not so large, $(m^o_t/m^o_{H_U})^2 \sim 20$. So the mass of H_U is negative[18,19].

If we suppose that the lightest charged leptons have masses of order 100 GeV, then Λ must be greater than about 30 TeV. In what follows, we will suppose that Λ^2 is of order the Goldstino decay constant, F. This assumption is the most natural one, but it should be kept in mind that the scale can be substantially larger. Indeed, in many existing models this scale *is* larger by an orders of magnitude or more. We will see that the phenomenology of the theory depends sensitively on the value of F[20][21].

Phenomenologically, the most distinctive feature of these models is that the LSP is the gravitino. The next to lightest supersymmetric particle (NLSP) is typically a neutralino or charged, right-handed slepton. This particle will decay to its superpartner plus a gravitino, with a rate governed by low energy theorems. Over a large region of the parameter space, the NLSP is neutral, with a significant bino component. The lifetime is then given by[22]:

$$\Gamma(\tilde{B} \to G + \gamma) = \frac{\cos^2 \theta_W \ m^5_{\tilde{B}}}{16\pi F^2} \tag{7}$$

This translates to a decay length

$$c\tau \simeq 1.3 \times 10^{-2} \left(\frac{100 \text{ GeV}}{m_{\tilde{B}}}\right)^5 \left(\frac{\sqrt{F}}{100 \text{ TeV}}\right)^4 \text{cm} \tag{8}$$

In other words, for F up to about 1000 TeV, the decay occurs in the detector. For a significant range of F, there is the possibility of measuring displaced vertices[20][21]. Note that a formula like eqn. 7 will hold in *any* model of low energy supersymmetry breaking, so long as the NLSP has a significant gaugino component.

We have already heard a good deal at this meeting about the experimental signatures for

[3]These formulas predict a near degeneracy of the bino and the right handed sleptons. Important corrections due to operator renormalization and D terms have been discussed in [17].

such processes. Assume, for the moment, that the bino is the NLSP. Then in e^+e^- annihilation, bino pairs can be produced (with selectron exchange) leading to final states with two photons and missing energy. This process will be used during the upcoming LEP runs to set limits on the bino mass. Similarly, in $p\bar{p}$ collisions, one can produce various new particles, yielding final states with photons and missing energy. As has been discussed at this meeting in the talks by Conway, Kane and Thomas, there is a candidate event of this type in the CDF data sample. Thomas, in particular, has discussed in some detail the interpretation of this event within the framework of low energy supersymmetry breaking[23].

So far, we have discussed a particular model for the messenger sector. This model is highly predictive. But while events with photon pairs and missing energy seem to be a generic signature of low energy supersymmetry breaking, it is less clear that the detailed predictions for the spectrum are generic. It turns out, however, that if the underlying theory is weakly coupled, there are only a limited set of possibilities for the messenger sector. One can reason as follows:

- At tree level, there are some rules for the spectrum which insure, for example, that there is a squark with mass lighter than the u-quark[1]. As a result, SUSY breaking must be fed through loops.

- Some of the messengers must carry color, or the gluino is too light.

- Because the messenger fields are more massive than the weak scale by powers of α, they must fall in vector representations of $SU(3) \times SU(2) \times U(1)$.

- Unification requires that the messengers fit into complete $SU(5)$ representations.

- Requiring that no couplings blow up before the unification scale constrains the number of messengers. One can have at most four $5 + \bar{5}$'s, or one $10 + \bar{1}0$.

- The messengers must couple to singlets, with non-vanishing scalar and F-components.

In other words, the model we have written is the simplest of a narrow class of models. The modifications we have described here spoil the mass formula in detail, but not universality. There is one other possible modification of the theory which we have not yet considered.[4] In the simple model, we insisited that there was no mixing of messengers with ordinary matter fields. This can be enforced by discrete symmetries, but it is not necessarily true. For example, one can contemplate couplings such as

$$H_D \bar{d} y_d Q + H_D \bar{q} Y_d Q. \tag{9}$$

Such couplings do not alter the KM structure. But they do imply new contributions to squark and slepton masses. A simple one loop computation yields a negative mass shift:

$$\delta m^2 = -\frac{Y^2}{16\pi^2} \frac{(F^\dagger F)^2}{6M^6}. \tag{10}$$

These contributions are certainly non-universal. However, our experience with ordinary quarks and leptons suggests that at most one or two states would be significantly displaced from the positions implied by eqn. 5.

Finally, what if the supersymmetry breaking sector is strongly coupled? In this case, the rules are far less clear. For example, Seiberg[24] has taught us that theories in the infrared may look quite different than in the ultraviolet, so perhaps we should drop our insistence on asymptotic freedom. Also, in strongly interacting theories, it is not so clear how the mass formulas may look. For example, one might expect an equation like 4 to hold, but perhaps not with so many factors of 4π. In such theories, scalars might be lighter than gauginos.[5]

We have seen in recent years that low energy dynamical supersymmetry breaking is quite plausible. While we do not yet have a model which, like the original Weinberg-Salam model, is compelling in its simplicity, progress in the understanding of supersymmetric dynamics raise hopes

[4] The remarks which follow have been developed in discussions with Savas Dimopoulos, Yossi Nir, Yuri Shirman and Scott Thomas.

[5] I thank Scott Thomas for raising this issue, and for discussions.

that this will be achieved. Given that photons plus missing energy are a generic consequence of this framework, confirmation of the CDF observation would provide a strong impetus to find this model.

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